

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

PATENT APPLICATION

for

Work-space Pressure Regulator

Inventors: **Thomas Q. Gurski**

Christopher C. Langenfeld

Stanley B. Smith III

Attorney Docket: 2229/139

Attorneys:
BROMBERG & SUNSTEIN LLP
125 Summer Street
Boston, MA 02210
(617) 443-9292

WORK-SPACE PRESSURE REGULATOR

5

Technical Field

The present invention pertains to regulating the pressure in the work-space of a pressurized engine, such as a Stirling engine.

Background of the Invention

10 Stirling cycle machines, including engines and refrigerators, have a long technological heritage, described in detail in Walker, *Stirling Engines*, Oxford University Press (1980), and incorporated herein by reference. The principle underlying the Stirling cycle engine is the mechanical realization of the Stirling thermodynamic cycle: isovolumetric heating of a gas within a cylinder, isothermal expansion of the gas (during
15 which work is performed by driving a piston), isovolumetric cooling, and isothermal compression.

A Stirling cycle engine operates under pressurized conditions. Stirling engines contain a high-pressure working fluid, preferably helium, nitrogen or a mixture of gases at 20 to 140 atmospheres pressure. A Stirling engine may contain two separate volumes of
20 gases, a working gas volume containing the working fluid, called a work-space or working space, and a crankcase gas volume, the gas volumes separated by piston seal rings. The crankcase encloses and shields the moving portions of the engine as well as maintains the pressurized conditions under which the Stirling engine operates (and as such acts as a cold-end pressure vessel). A pressurized crankcase removes the need for high pressure sliding
25 seals to contain the work-space working fluid and halves the load on the drive component for a given peak-to-peak work-space pressure, as the work-space pressure oscillates about the mean crankcase pressure. The power output of the engine is proportional to the peak-to-peak work-space pressure while the load on the drive elements is proportional to the

difference between the work-space and the crankcase pressures. Figure 1 shows typical pressures in the gas volumes for such an engine.

The action of the piston rings can raise or lower the mean working pressure above or below the crankcase pressure, substantially mitigating the above-mentioned advantages of a 5 pressurized crankcase. For example, manufacturing marks, deviations and molding details of the rings can produce preferential gas flow in one direction between the work-space and the crankcase. The resulting difference in pressure between the work-space and the crankcase can produce as much as double the load on engine , while peak-to-peak pressure and thus engine power increases only fractionally (see, e.g., fig. 2). In summary, pumping 10 up the workspace mean pressure significantly increases engine wear with only a small attendant increase in power production.

Summary of the Invention

In embodiments of the present invention, a device is provided that reduces the mean pressure difference between a work-space and a pressurized engine crankcase of an engine, 15 such as a Stirling engine. The device includes a valve connecting the work-space and crankcase of the engine. The pressure difference between work-space and crankcase is monitored. When the mean pressure of the work-space differs from the crankcase pressure by a predetermined amount, the valve opens, allowing the pressure difference between the two spaces to equalize. When the pressure difference between the spaces is reduced 20 sufficiently, the valve closes, isolating the work-space from the crankcase. This closure maximizing power production, while minimizing wear on drive components.

In a specific embodiment of the invention, pressure at which the valve opens is determined by a preloaded spring. In a further specific embodiment of the invention, the mean pressure is monitored by including a constriction in the passageway from the valve to 25 the work-space so that a mean work-space pressure is presented to a pressure monitoring device. In a further specific embodiment of the invention, the device further includes a constriction in the passageway from the crankcase to the pressure monitoring device such that the monitoring device is presented with a mean crankcase pressure.

Brief Description of the Drawings

The invention will be more readily understood by reference to the following description, taken with the accompanying drawings, in which:

Fig. 1 shows a graph of work-space and crank-case pressure for a Stirling engine
5 with a pressurized crankcase;

Fig. 2 shows a graph of pressure between a work-space and a crankcase for a Stirling engine when the work-space is pumped-up;

Fig. 3 shows a side view in cross section of a sealed Stirling cycle engine;

Fig. 4 shows a pressure regulator for an engine according to an embodiment of the
10 invention;

Fig. 5 shows a pressure regulator for an engine according to another embodiment of the invention;

Fig. 6 shows a pressure regulator for an engine according to a further embodiment of the invention; and

15 Fig. 7 shows the pressure difference that may develop across a valve according to the embodiment shown in fig. 6.

Detailed Description of Preferred Embodiments

In embodiments of the present invention, a device is provided that reduces the pressure difference between a work-space and a pressurized engine crankcase of an engine,
20 such as a Stirling engine. Referring to fig. 3, a sealed Stirling cycle engine **50** is shown in cross section. While this embodiment of the present invention will be described with reference to the Stirling engine shown in fig. 3, it should be understood that other engines, coolers, and similar machines may likewise benefit from embodiments of the present invention and such combinations are within the scope of the invention, as described in the
25 appended claims. A sealed Stirling cycle engine operates under pressurized conditions.

Stirling engine **50** contains a high-pressure working fluid, preferably helium, nitrogen or a mixture of gases at 20 to 140 atmospheres pressure. Typically, a crankcase **70** encloses and shields the moving portions of the engine as well as maintains the pressurized conditions under which the Stirling engine operates (and acts as a cold-end pressure vessel.) A heater
30 head **52** serves as a hot-end pressure vessel.

Stirling engine **50** contains two separate volumes of gases, a working gas volume **80** and a crankcase gas volume **78**, that will be called hereinafter, a “work-space” and a “crankcase,” respectively. These volumes are separated by piston rings **68**, among other components. In the work-space **80**, a working gas is contained by a heater head **52**, a regenerator **54**, a cooler **56**, a compression head **58**, an expansion piston **60**, an expansion cylinder **62**, a compression piston **64** and a compression cylinder **66**. The working gas is contained outboard of the piston seal rings **68**. The crankcase **78** contains a separate volume of gas enclosed by the cold-end pressure vessel **70**, the expansion piston **60**, and the compression piston **64**. The crankcase gas volume is contained inboard of the piston seal rings **68**.

In the Stirling engine **50**, the working gas is alternately compressed and allowed to expand by the compression piston **64** and the expansion piston **60**. The pressure of the working gas oscillates significantly over the stroke of the pistons. During operation, fluid may leak across the piston seal rings **68** because the piston seal rings **68** do not make a perfect seal. This leakage results in some exchange of gas between the work-space and the crankcase. A work-space pressure regulator (“WSPR”) **84** serves to restore the pressure balance between the work-space and the crankcase. In embodiments of the invention, the WSPR is connected to the work-space by passageway **82**, which may be a pipe or other equivalent connection, and to the crankcase by another passageway **86**. When the work-space mean pressure **80** differs sufficiently from the mean crankcase pressure, the WSPR connects the two volumes via vent, **88** until the differential between the mean pressures diminishes.

For example, an exemplary work-space pressure regulator is shown in fig. 4. Pipe or passageway **82** connects the pressure regulator **84** to the work-space **80**. A restrictive orifice **92** damps the oscillating work-space pressure applying the mean work-space pressure to one end of the shuttle, **100**. The orifice **92** is sized to be significantly larger than the piston seal ring leak. As used in this specification including any appended claims, the term “constriction” will be used to denote a narrowing in a pipe or passageway, including such a constriction at the end of a pipe or passageway or any place within the pipe or passageway. The other end of the shuttle **100** is exposed to the crankcase pressure via a pipe **86**, which pipe may include a restrictive orifice **93** or other constriction. Orifice **93** may be sized much

smaller than orifice 92, in which case the combination of the shuttle 100 and the orifice 93 act to damp movement of the shuttle from work-space pressure swings applied through orifice 92. In a specific embodiment of the invention, orifice 92, from WSGR to work-space is approximately .031 inches in diameter, while orifice 93, from WSGR to the crankcase, is 5 approximately .014 inches in diameter. In other embodiments of the invention, the constriction from shuttle to crankcase may be omitted. Note that the crankcase pressure is approximately constant over the piston's cycle, while the work-space pressure swings significantly during the cycle. Two springs 102, 104 keep the shuttle 100 centered, when the mean work-space and the crankcase pressures are equal.

10 When the mean work-space pressure is higher than the crankcase pressure, the higher pressure moves the shuttle 100 to the right, compressing spring 104. If the pressure difference is large enough to expose port 88 the work-space and the crankcase become connected. Some of the work-space gas flows into the crankcase until the two mean pressures are equalized, which allows the shuttle 100 to return to the original position, 15 closing the port 88. Note that orifice from the work-space to the WSGR 92 may be sized to allow the pressure to equalize between work-space and crankcase quickly when port 88 is exposed, while still small enough to present a mean work-space pressure to the shuttle 100.

When the mean crankcase pressure is higher than the work-space pressure, the shuttle will move to the left, compressing spring 102. If the pressure difference is large enough, port 20 88 will be exposed to channel 112, connecting space 94 with the crankcase 78. Some of the crankcase gas flows into the work-space until the two mean pressures are equalized, which allows the shuttle 100 to return to its centered position, closing port 88.

The shuttle isolates the work-space 80 from the crankcase 78 in its centered position. The seal may be provided by two cup seals 122 located at the end of shuttle nearest the 25 crankcase vent 86 or by equivalent seals as are known in the art. Two ring seals 120 center and guide the shuttle 88 in the WSPR body 114.

Another embodiment of the invention is shown in fig. 5 and labeled generally 200. Work-space housing 205 and crankcase housing 210 are bolted together capturing piston 215, work-space spring 225, and crankcase spring 230 in their bores. The interface of the 30 two housings creates cup seal gland 260 into which seats a bi-directional cup seal 220, and an O-ring gland 265 into which seats an O-ring 270. The O-ring seals the interior of the

5 housings from the crankcase pressure. Two orifices **235** allow the pressures inside the two housings to remain equal to the mean crankcase pressure and the mean work-space pressure, respectively, without large pressure oscillations or large mass flows into/out of the housings. The piston is free to move axially within the housings by sliding on its bearing surfaces **250**.

10 When the two pressures are equal, the springs keep the piston centered such that the cup seal seals against the piston's sealing surface **255**, preventing any flow between the two housings. When the pressure differential between the two housings becomes great enough, the force imbalance on the piston will cause the piston to move away from the region of high pressure, compressing the spring on the low-pressure side and relaxing the spring on the high-pressure side. Equilibrium is reached when the pressure force imbalance equals the spring force imbalance. If the pressure differential is great enough, the piston will be displaced enough that the cup seal **220** no longer contacts the sealing surface and instead loses sealing force against the decreasing diameter of the piston. Once the seal is broken, gas can flow from the high-pressure side, through the vent hole **240** or vent slot **245**, past the cup seal **220**, and into the adjacent housing. Gas will continue to flow until the pressure has equalized enough for the springs to return the piston to a position where the cup seal **220** seals against the sealing surface **255**.

15 Another embodiment of the invention is shown in fig. 6 and will be referred to as the Preloaded WSPR (**300**). This embodiment of the invention uses preloaded springs **302**, **304** connected to an inner piston **340** and an outer piston **342** to control working gas flow into and out of the work-space **80**. The springs are open-coil springs and, thus, gas flows freely through these springs. WSPR **300** communicates with the work-space **80** via an orifice **392**. Likewise, the crankcase volume **78** is connected to WSPR **300** via port **393**. Work-space pressure oscillations are damped out by the constriction of the orifice **392** together with the force of the pre-loaded springs **302**, **304** acting on the pistons **340**, **342**. Seals **370**, **372** provide a compliant seat for pistons **340**, **342**. The orifice **392** is sized to be significantly larger than the piston seal ring leak. WSPR **300** may be mounted on the compression cylinder head of the engine **58** (see fig. 3).

20 The Preloaded WSPR relieves a mean overpressure in the work-space in the following manner. The oscillating work-space pressure, which is partially damped by the orifice **392**, is applied to the face **380** of the inner piston **340** and to the face of the outer

piston 342 that are proximate to the work-space. If the net mean pressure on the pistons is enough to overcome the preload on spring 302, then the inner and outer pistons move to the left and open the valve at 382. The released gas flows past the open seal at 382 around the outside of the outer piston 342, through spring 302 and into the crankcase via port 393.

- 5 Once the difference between the work-space and the crankcase pressures drops below the preload on spring 302, the outer piston 342 moves back to the right and seals at 382. Seal 372 provides a compliant seat for piston 342.

The Preloaded WSPR relieves excess crankcase pressure by a similar method. When the net pressure times the inner piston's 340 area is greater than the preload on spring 304,

- 10 the inner piston 340 moves to the right and opens the valve at 370, which provides a compliant seal for the inner piston 340. Gas from the crankcase flows between the outer and inner pistons and into the work-space via the orifice at 392 reducing the pressure differential. Once the difference between the work-space and the crankcase pressures drops below the preload on spring 304, the inner piston 340 moves back to the left and seals at 370.

- 15 In another preferred embodiment of the invention, the preloads in springs 302 and 304 may be preloaded to different force levels. The different forces applied by the springs would allow the workspace pressure to "pump-up"(i.e., increase) reaching a higher mean pressure, thereby allow the engine to produce higher mechanical power. This embodiment allows the design to add engine power without raising the crankcase mean pressure. Thus 20 the power can be increased without redesigning or perhaps requalifying the crankcase pressure vessel.

- 25 The functioning of the Preloaded WSPR can be understood by considering the pressures difference between the two orifices 392 and 393 in fig. 6. As an example, consider the pressure across valve 310, as shown in fig. 7. (It should be noted that fig. 7 is exemplary only and does not represent measured data on a WSPR.) The pressure difference between the two orifices can be better described as the pressure difference across regulator valve 310 where the regulator valve is composed of the two pistons 340, 342, the two springs 302, 304 and the two valve seats 370, 372. Fig. 7 shows the pressure across valve 310 for two cases. In one case, the preload on each spring 302, 304 is the same, and the workspace does not 30 "pump-up," as shown by graph 402. The workspace and crank case remain at approximately the same mean pressure. In the second case, the preload on spring 302 is greater than the

preload on spring **304**. Graph **404** shows the pressure across the valves, when the workspace has a mean pressure that is 100 psi above the crankcase pressure. In the latter case, the pressure difference may become large enough to overcome the preload on valve **302**, opening valve **310** and allowing gas to flow out of the workspace into the crankcase,

5 reducing the pressure in the workspace. The horizontal line in fig. 7 shows the pressure at which the preload on spring **304** is overcome. At that pressure, the WSPR opens allowing gas to pass between workspace and crankcase. The devices and methods described herein may be used in combination with components comprising other engines besides the Stirling engine in terms of which the invention has been described. The described embodiments of

10 the invention are intended to be merely exemplary and numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in the appended claims